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3D Printing for Sustainable Construction

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ABSTRACT: Sustainability is interpreted as the effective use of resources as well as the preservation of the environment. A sustainable building is giving back to the environment more than it takes and ensuring that the resources is being used in an effective way that would benefit the community. A combination of smart design, efficient technology and designing buildings with sustainability in mind from the start of the designing phase is therefore necessary. 3D concrete printing can be a sustainable solution because of its ability to manufacture complex shapes to enable passive design thus reducing energy consumption. This article presents an overview on the sustainability of 3D concrete printing in terms of printable green materials as well as sustainable architectural design to achieve passive system.

1 INTRODUCTION

3D concrete printing, also known as additive manufacturing in the building industry, is expected to be a true game-changer in Industry 4.0. The potential of this technology when it reaches maturity can revolutionize the construction market and make major changes such as shorter building time, cheaper construction, freedom of shape and integration of functionality (Kothman & Faber 2016). In addition, the correct use of green materials and selection of sustainable complex architectural design can amplify the sustainability of this technology. s

1.1 *3D concrete printing and printable material*

3D concrete printing has two main different techniques to create complex structure: Binder jetting and material deposition method (Tay et al. 2019a). Both of these methods create a complex structure by adding small layers of material over the previous layer. However, the latter technique seems to be more favourable in the field of research in terms of publication (Tay et al. 2019a). Its paradoxical rheological property is one of the challenges to be addressed before successful printing can be possible.

The rheological performance of a printable concrete material is different from the conventional casted material. For material to be printable, it has to be flowable so that it can be delivered to the nozzle by a pump (Roussel 2018). Furthermore, after extrusion, it has to be stiff enough to hold its shape and the weight of the subsequent layers (Tay et al. 2019a). Whereas, in the conventional casting technique, the formwork will hold the fresh concrete in place. Lastly, the interlayer bonding between the layers, which is a distinct feature compared with conventional casted concrete, should be strong enough to sustain the structures. These interfaces between layers tend to be the weakness of the whole structure (Tay et al. 2019b).

1.2 *Sustainable construction*

Sustainable construction is the aim to meet present-day needs for infrastructure, housing and working environments without compromising the ability of future generations to meet their own needs in times to come. This means ensuring that resources are being used in an efficient way that would benefit the community and the world.

Several sustainable materials that have a low carbon footprint can be used for 3D printing. Fly ash, geopolymer and recycled glass are some of the green material that has been used by the industry (Panda et al. 2018). Although these sustainable materials have been used in conventional casting methods, the rheological behaviour for printing is different. The mixtures have to be tailored to this new manufacturing process for printing to be successful. Apart from printing sustainable materials, printing passive design maximizes the potential of 3D printing to create comfortable space for the users. A passive system is a combination of energy-efficient design to take advantage of the climate to maintain the comfort level in an infrastructure. Such an approach reduces energy consumption during operation. However, the passive design has to be implemented during the design phase.

Sustainable construction is a broad term and can involve different types of issues (Tan et al. 2011). The focus of this paper is the sustainability of 3D concrete printing in terms of construction material and architectural design to improve the way people build and live in the building sector.

2 SUSTAINABLE PRINTABLE MATERIALS

The materials presented below are the green materials currently under research at SC3DP, NTU, Singapore. The usage of these materials is considered sustainable since dumping to a landfill will cause a negative environmental impact. These researches revolve around investigating a suitable mixture ratio to fulfil the required behaviour for printing.

2.1 *High volume fly ash concrete*

Fly ash-based materials are one of the possible alternatives for printing sustainable concrete structures. Fly ash is a by-product from the coal industry and is considered as a waste product. It contains some toxic metals that will degrade the soil and will cause air pollution. As such, a research carried out SC3DP, NTU offers suitable high-volume fly ash based formulation for 3D printing application which can reduce the environmental impact instead of disposing them to an open environment (Panda et al. 2018). Hence, a high volume of fly ash was incorporated in the formulation and it was found to improve long term strength performance of the building materials.

The rheological properties of the printable material in its fresh state is crucial. High thixotropy behaviour allows the material to become less viscous when stress is applied and allow it to return to its more viscous state when at rest. It can be measured in terms of structural breakdown and recovery. A shear-thinning protocol was used to calculate a structural index, λ, by shearing the mortar at 300 s^{-1} for 300 seconds. In general, the higher the λ, the higher the thixotropy. The result is shown in Figure 1a. It can be seen that the structural index of the material increased with resting time. This phenomenon was linked to both the physical interaction of the particles and the hardening process (Panda et al. 2019).

Additionally, the viscosity recovery was measured to investigate the fresh property of the mortar after the extrusion process. If the original viscosity of the initially deposited layer has not recovered before the deposition of the second layer, it may cause deformation in the printed structure. the protocol for this second test is as follows: (i) $0.01s^{-1}$ for 60 seconds; (ii) $300s^{-1}$ for 30 seconds and; (iii) $0.01s^{-1}$ for 60 seconds. These three different intervals correspond to the material state (i) initially at rest; (ii) extrusion and (iii) at rest after extrusion. The result is shown in Figure 1b. Almost 80% of fly ash was utilized to formulate the mix design that exhibits excellent thixotropic behaviour and achieving 35Mpa mechanical compressive strength, which is suitable for non-structural application (Biranchi Panda et al. 2019).

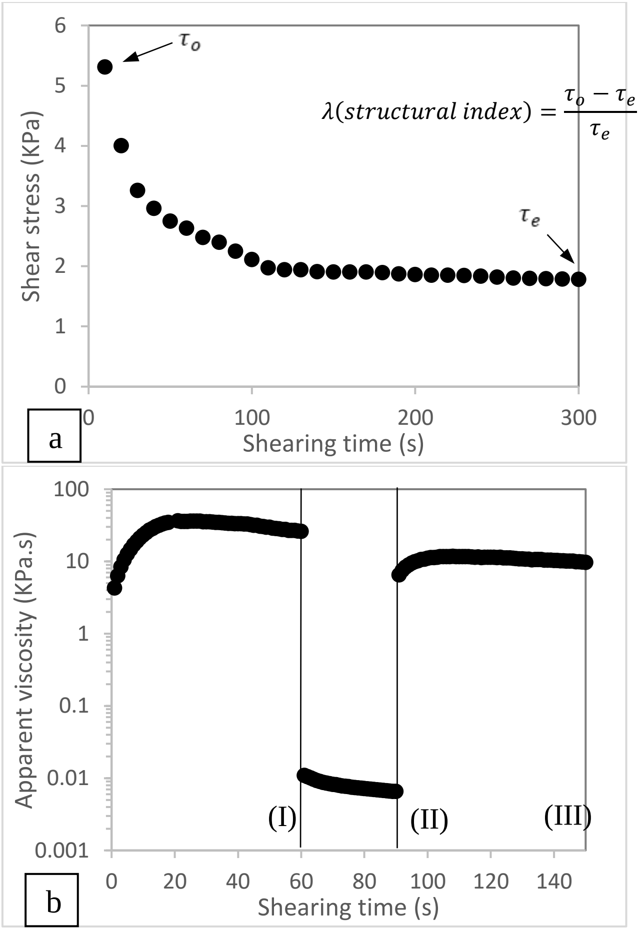


Figure 1. Thixotropy behaviour of 3D printed concrete (a) structural breakdown (b) structural recovery.

Furthermore, this mixture is used to print a modular toilet shown in Figure 2a. The toilet was printed in three parts and later assembled on site. Comparing to the conventional method of creating concrete structures, 3D concrete printing can save the material wastage, production time, cost and ultimately fetch sustainability in our built environment.

2.2 *Geopolymers*

3D printing with high volume fly ash is a challenge as the strength development in an early age is not quick enough to support subsequent layers. To avoid this problem, fly ash was activated with an alkali solution according to geopolymerization mechanism. Figure 2b shows an example 3D printing of geopolymer mortar extruded through a rectangular orifice of a 4-axis gantry printer. To enhance the reaction process, 5-10% slag, which is also regarded as one of the by-products of steel power plant industries, was used.

Figure 2. (a) 3D printing of modular toilet with high volume fly ash at SC3DP, NTU. (b) 3D printing of geopolymer.

2.3 *Recycled glass aggregates*

Despite the abundant supply of sand from the desert or the seabed, the world is facing a shortage of construction sand. This is mainly due to the nature of the desert sand and sea sand are not suitable for applications in construction, thus, only river sands are used in the construction industry. Hence, with the limited resource for construction sand, an alternative solution is needed to meet the increasing demand for construction materials. Singapore generates over 70,000 tons of glass waste annually, in which only less than 20% is being recycled (National Environment Agency 2018). The remaining waste glass is usually disposed of in landfill where it is not suitable due to its non-biodegradable nature. The study of replacing river sand by the recycled glass in cementitious materials has been established for decades.

At SC3DP, NTU the research on using recycled glass aggregates for 3D concrete printing focuses on the formulation of mix design and the effect of recycled glass aggregate gradation on printability (Ting et al. 2018). The comparison of the river sand and recycled glass aggregates was studied to evaluate the printability performance of the materials. The gradation study of the recycled glass particles was also conducted to optimize the material performance for 3D concrete printing application. Furthermore, the alkali-silica reaction which is a commonly known issue in the recycled glass aggregates is currently being investigated.

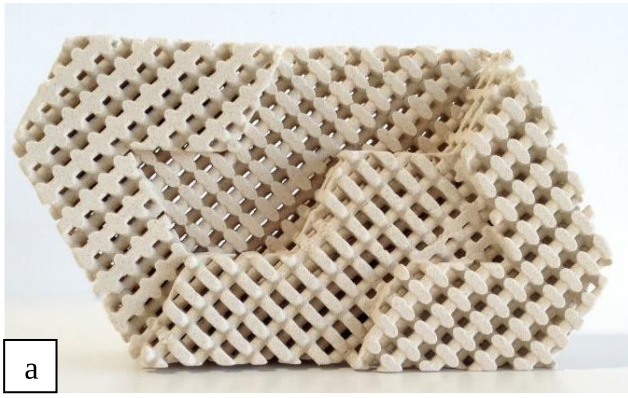
3 SUSTAINABLE ARCHITECTURAL DESIGN

Construction sustainability does not necessarily relate only to the selection of green materials. The energy used in the fabrication process, and the energy used in its operation after construction is equally important. The implementation of passive designs can dramatically reduce energy consumption and is an area where 3D concrete printing can potentially make a significant contribution because of the ease of creating a complex structure.

3.1 *Management of passive cooling or heating effect*

In warm climates, maximizing the use of natural airflow can contribute significantly to the energy load of the building. Excessive usage of air conditioning due to poor cooling efficiency design is not desirable. Clever designs such as “Cool Brick” can help in passive cooling (Fratello & Rael 2015) as shown in Figure 3a. This use of natural cooling effect must be incorporated in the design stage. In cold climates, the same principle should be applied in designing the insulation that could retain and recirculate the heat with minimum energy used.

The complexity of the shapes that can be printed by 3D printing is endless. The modular wall shown in Figure 3b is made up of modular blocks. These modular blocks can allow passive cooling and maximize the use of natural airflow while providing shade from the sunlight. Furthermore, such a design improves the appearance of the wall.




b

Figure 3. (a) Brick that provides passive cooling made by additive manufacturing (Fratello et al., 2015) (b) 3D printed modular wall printed in SC3DP, NTU.

3.2 *Management of natural lighting effect*

Management of natural lighting is another important aspect. While the type of material and building orientation can achieve natural lighting, using additive manufacturing can control the lighting permeability while improving the appearance of the wall. Small modular blocks can be printed to control the amount of light allowed to be pass through as shown in Figure 4 (Stott 2015). Indoor spaces that are naturally brightened can reduce the need for artificial lighting at a later stage. Such designs of using natural lighting need to be considered in the early stages of the designing process.

Extrusion over a doubly curved surface can be achieved with 3D printing without the need for formworks. Research work carried out in SC3DP, NTU printed the framework and was later assembled to form the curve bed for printing. The wireframe is then covered with a flexible textile to provide a surface for printing as shown in Figure 5. This printing serves as a proof of concept to build larger modular curved facades and complex architectural shape which can then be used for controlling the natural light.

Figure 4. Structure printed in modular that have different light permeability (Stott 2015).

Figure 5. Curved bed printing with printed frames printed in SC3DP, NTU.

3.3 *Management of acoustic effect*

Dampening the sound surrounding the building or within the premises can improve the comfort of the user. Using passive designs can reduce the need for additional material for soundproofing. Figure 6 shows an element that was designed to enhance the soundproofing capability of a wall (Gosselin et al. 2016). The generic elements were stacked together to form a complete wall. The geometries of the holes dampen the acoustic waves passing through.

Figure 6. Concrete printed acoustic wall element (Valente et al. 2019).

3.4 *3D printing optimized concrete structure*

Beyond economical and architectural benefits, 3D concrete printing can be used to reduce the environmental footprint of the industry. The increased level of control offered by 3DCP enables the use of the advanced computational algorithm to reduce the density of the structure by creating a lattice structure. These optimized structures (See Figure 7) not only reduce the overall weight but also improve the use of resources effectively. In addition, it can incorporate structural members such as rebar, pre-stressing cable to produce structural concrete (Lim et al. 2018). 3D printed pedestrian bridge (Salet et al. 2018) is one of the recent examples, where the printed structure was post-tensioned after assembling the individual 3D printed sections.

It is worthy to note that, the traditional optimization software only considers isotropic material properties during the analysis, however for 3D printing projects the part design needs to be finalized whilst taking the properties and limitations of a 3D concrete printer and the material properties into account.

Figure 7. 3D printed lattice shape wall element printed in SC3DP, NTU.

4 CONCLUSIONS

3D concrete printing is a promising technology to address the sustainability challenges in today's construction industry and open up new opportunities for design possibilities. The future of construction is most likely to be an integrated process that allows the organization to take advantage of both conventional and additive manufacturing technologies.

With rapid urbanization in many developing countries, there is an urgent need to come up with clever ideas that optimize the sustainable performance of the buildings that we live and work in.

Construction firms today need to recognize that sustainable construction is becoming a greater concern. Builders who invest in the latest sustainable technologies in the construction process can recoup those costs over time in the form of decreased building operation costs as a result of greater energy efficiency. Regulators also play a significant role in sustainable construction by creating the right incentives for companies that choose to build sustainably. Finally, the government can legislate and create mandates that require firms to build in a sustainable way.

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